SWCNT NanoCompass for Next-Generation Magnetometry

presented by
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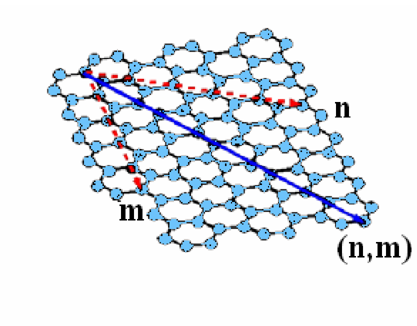
Outline

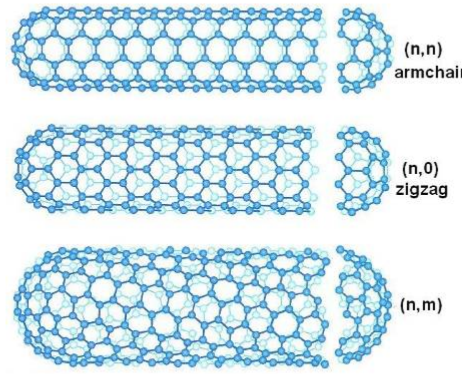
- Background (carbon nanotubes)
- Magnetometer applications
- Technological motivation
- NanoCompass design and fabrication
- SWCNTs as a suitable material for magnetometry
- NanoCompass prototypes
- Conclusions and future work

Carbon Nanotubes (CNTs)

• Characterized by chirality, diameter



Courtesy Fuhrer Group, Univ Maryland, College Park



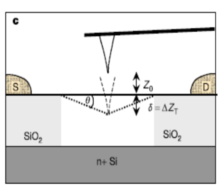
Courtesy Smalley Group, Rice Univ.

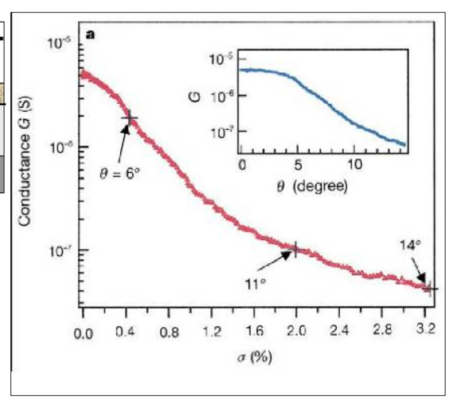
Metallic SWCNT:

n – m = 3 x integer

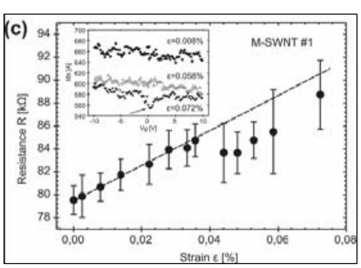
CNT Strain Sensor

• Modulation of conductance by mechanical deformation





Tombler *et al.*, *Nature* **405**, 769 (2000).



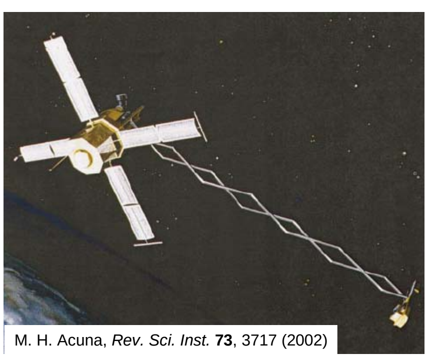
C. Stampfer *et al.*, *Nano Lett.* **6**, 233 (2006).

Magnetometer Applications

- **Spaceflight Applications**
  - Magnetospheric science
  - Spacecraft orientation
  - Planetary geomagnetism
  - Navigation
- **Terrestrial Applications**
  - Military and homeland security
  - Oil, gas, and nuclear industries
  - Health care diagnostics
  - Current sensors/probes for electronics
  - MICR readers and RFID tags
  - Calibration of laboratory field sources
  - Ore analysis

Technological Motivation

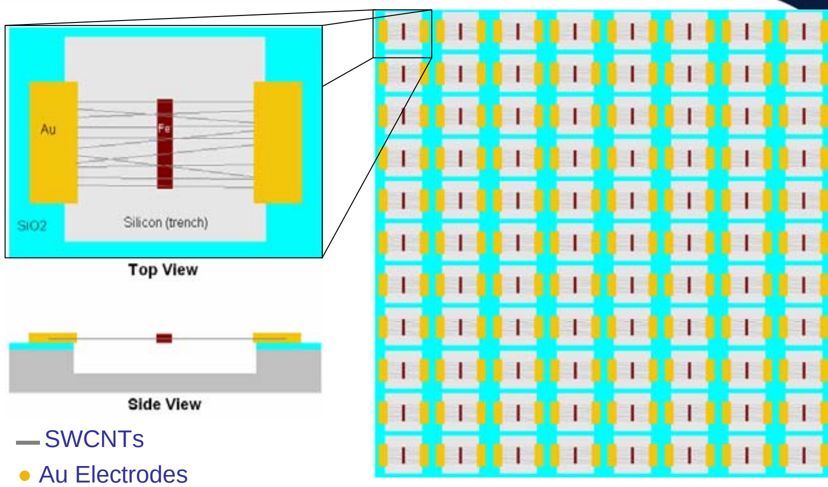
- Fluxgate magnetometer is ubiquitous in spaceflight:
  - High sensitivity (nanoTesla)
  - Low noise



M. H. Acuna, *Rev. Sci. Inst.* **73**, 3717 (2002)

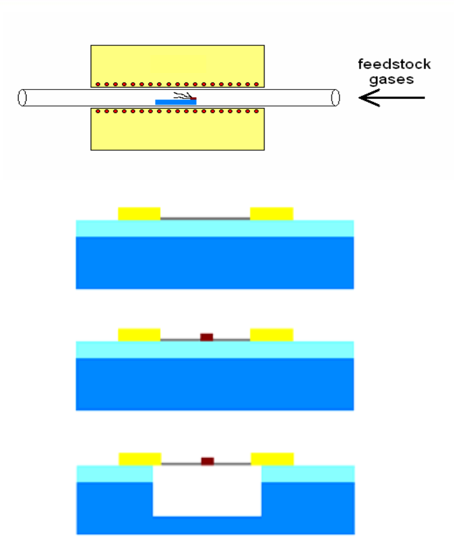
- Limitations
  - cm-scale resolution
  - Limited materials supply
  - Boom-mounted → low mass is beneficial

NanoCompass Design



- SWCNTs
- Au Electrodes
- Ferromagnetic Needle
  - Mech coupled to SWCNTs
  - Deflected in Magnetic Field

NanoCompass Fabrication



Step 1: Grow SWCNTs by catalyst-assisted CVD growth

Step 2: Pattern/deposit Au electrodes

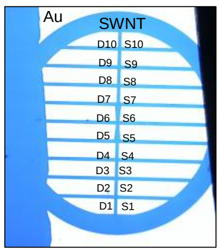
Step 3: Pattern/deposit Cr/Fe/Cr needle

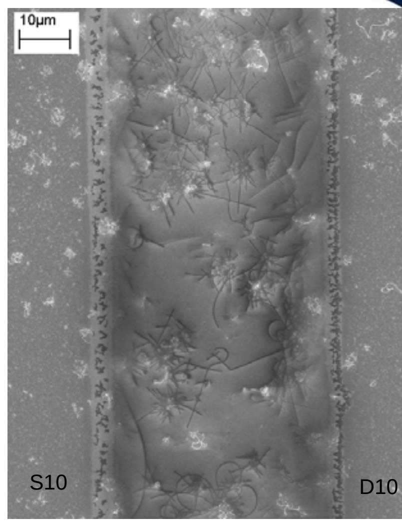
Step 4: Pattern/etch trench in SiO_2/Si to release

Precursor Device: Bound to Substrate

- Catalyst = $Fe(NO_3)_3$
- T_G = 850°C
- Cr/Au electrodes

flow





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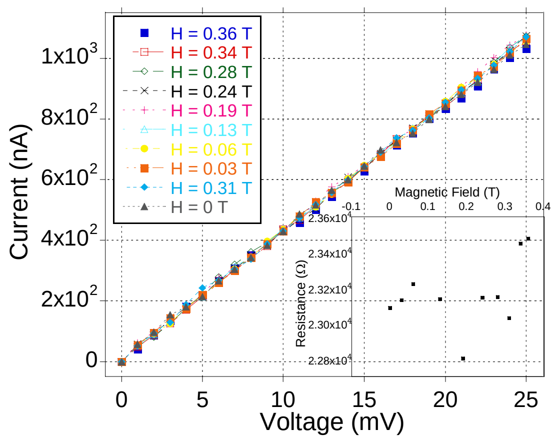
Magnetic Field Measurements



- SWCNT resistance insensitive to low magnetic field
  - Fe catalyst oxidized, well spaced
- Magnetometer operation: Strain mechanism will dominate

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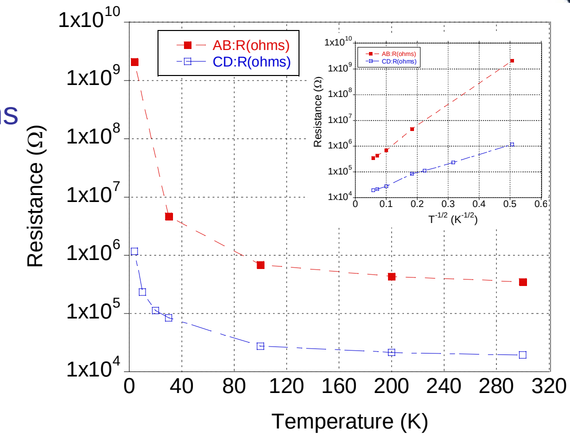
Temperature Dependence

- Strong low-T dependence
- Barrier(s) present
  - Inter-tube junctions
  - Electrodes
- Stable operation T > 100 K
  - Minimal thermal control required



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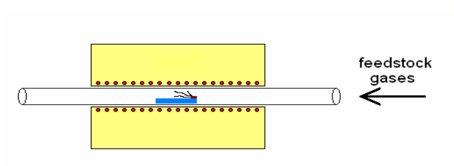
NanoCompass Fabrication



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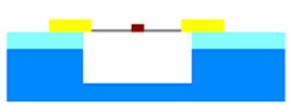

Step 4: Pattern/etch trench in SiO_2/Si to release

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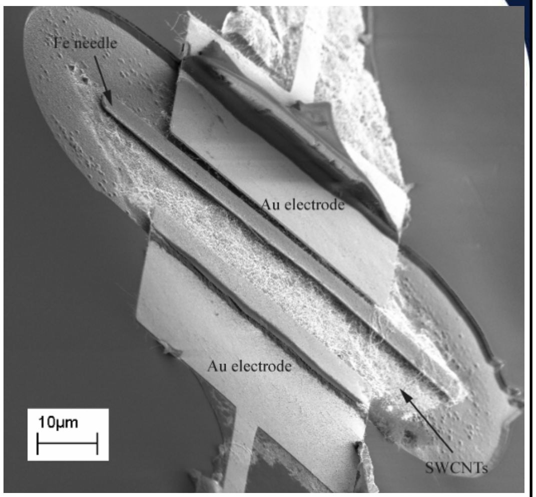
NanoCompass Prototype 1

- Materials withstand fabrication process
- Next steps:
  - Reduce electrode spacing
  - Reduce needle width
  - Increase trench depth



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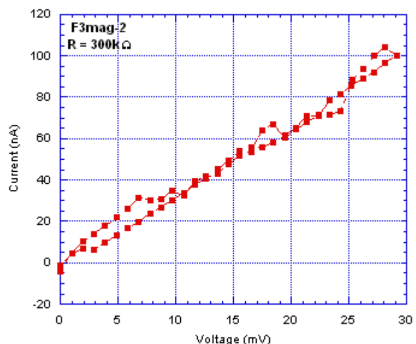
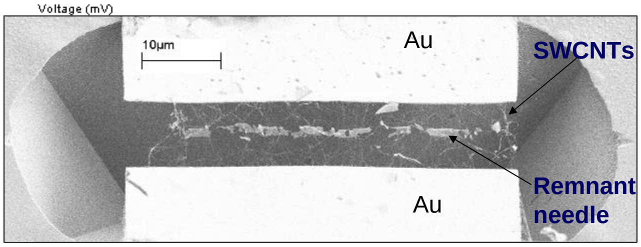
NanoCompass Prototype 2



- SWCNT device electrically intact
- During magnetic field testing, continuity lost
- Next prototype in process



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Future Work/Partnership Opportunities

- Magnetometer prototype fabrication complete
  - Materials are compatible with processing
  - Next prototype under development
- Technology transfer
  - Can be licensed for commercial applications
  - http://ipp.gsfc.nasa.gov/ft-tech-NanoCompass.html
- Collaborators for systems-level component and packaging
  - Compact, low-power electronic instruments (e.g., power supply, lock-in amplifier)
  - Robust packaging approaches
  - Microfabrication of hard magnets

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Acknowledgements

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- ***Brigham Young University***
  - Prof. David Allred
  - Prof. Richard Vanfleet
  - Johnathan Goodsell
  - Jonathon Brame
- ***Fisk University***
  - Melissa Harrison

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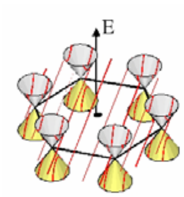
Electronic Properties: CNTs

- Metallic or Semiconducting

Radial Boundary Conditions

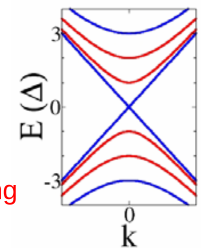
→ Wavevector quantization



<u>Discrete Bands</u>

❖ Metallic

❖ Semiconducting



Difficult to control → trend towards CNT network devices

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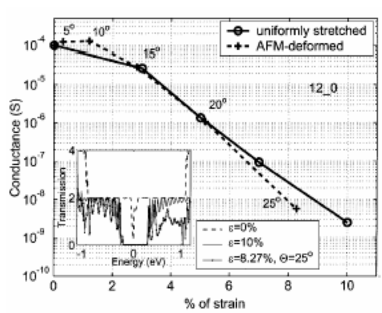
CNT versus Silicon

CNTs
Δ ~ 4 *orders of magnitude*
for θ ~25º



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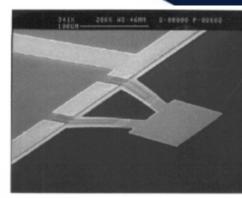

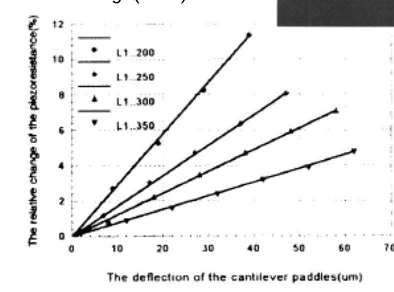

Silicon piezoresistors
Δ ~12% for θ ~30º

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Projected Specifications

	NanoCompass (estimated)	**UCLA fluxgate (ST5)**
Max Op Temp	~450°C	100°C
Sensor Dimensions	10^{-5} cm x 10^{-5} cm on Si (scalable)	4 cm x 4 cm x 6 cm
Sensor [Array] Mass	1 g	75 g
Sensor Op Power	10^{-3} – 10^{-2} mW	50 mW

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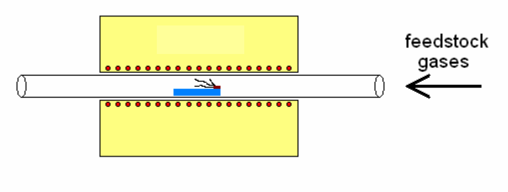
Vapor-Liquid-Solid Growth

- Feedstock gas → liquid alloy → solid nanostructure



SWCNTs:

- Catalyst = $Fe(NO_3)_3$:IPA
- Feedstock = CH_4 and C_2H_4
- T_G = 850°C

- Catalyst = thin film Fe
- Feedstock = CH_4 and C_2H_4
- T_G = 950°C

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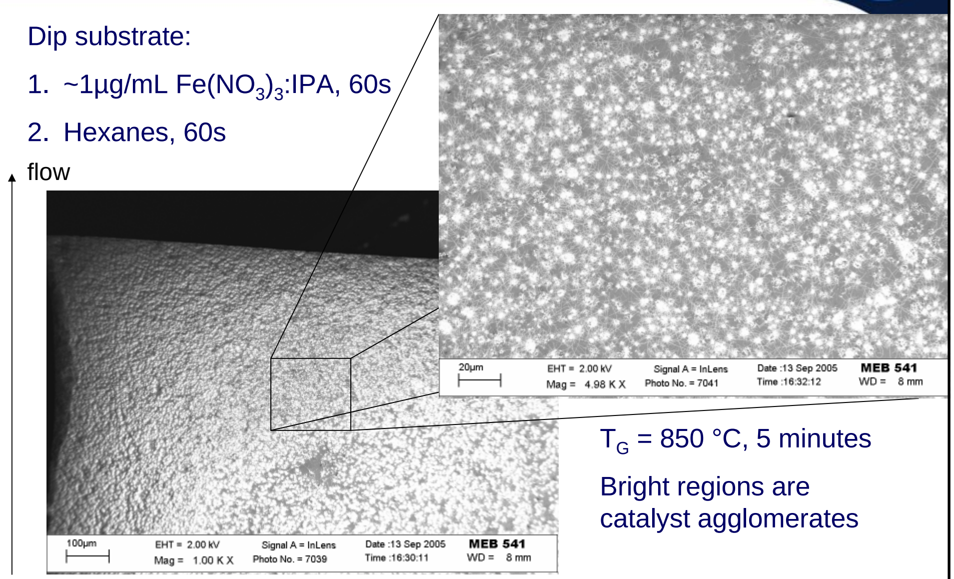
$Fe(NO_3)_3$ Catalyst

Dip substrate:

1. ~1µg/mL $Fe(NO_3)_3$:IPA, 60s
2. Hexanes, 60s



T_G = 850 °C, 5 minutes

Bright regions are catalyst agglomerates

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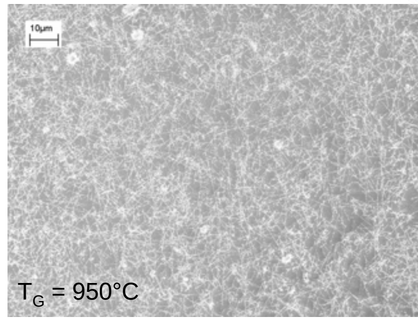
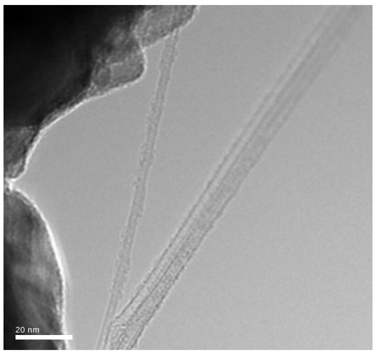
Thin Film Fe Catalyst

- High density
- Improved cleanliness





- TEM studies show
  - SWCNTs
  - MWCNTs
  - bundles

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